Flood forecasting

by Carlos E.M. Tucci and Walter Collischonn*

Introduction

Forecasts of a river flow can be made in the short-term, over periods of a few hours or a few days of lead time and, in the long-term, up to nine months (Georgakakos and Krysztofowicz, 2001). Usually, short-term flow forecasts are used for flood management, but there are many other contexts in which they are useful, such as navigation in rivers where the load transported is dependent on the depth of water in unregulated rivers, irrigation and water supply, and integrated uses such as flood warning and prevention and hydropower.

Short-term flow forecasting is developed continuously or only after a hazardous situation. The former is usually required for operational purposes, such as hydropower and navigation. It can be classified according to required lead time or basin time response to rainfall.

Flash floods

Flash floods have a very short lead time and are a combination of a meteorological event, usually related to a convective storm, with a particular hydrological situation, such as a small basin, steep slope or low infiltration capacity. This type of forecasting is strongly dependent on the quantitative precipitation forecast (QPF), since the time between rainfall and peak flow is very short for warning and relief measures during a flood (Krysztofowicz, 1995). Georgakakos and Hudlow (1984) mentioned that 25 per cent of communities across the USA have a lag time of less than four hours between rainfall and flow from the basin.

Flash floods are usually related to rural basins but, in large cities (e.g. São Paulo, Buenos Aires, Barcelona), with the increase of impervious and natural creeks being changed to channels and pipes, the time of concentration decreases and increases the peak flow. Managing the urban drainage system of conduits and controlling the traffic on days of heavy rain during the wet season require a warning system based on a quick evaluation and forecast. In Brazil, the city of São Paulo uses radar and an empirical relationship between radar frequency and flood conditions of the city's main drainage channel to alert and organize the city traffic.

Medium- and large-basin flood forecast

Medium and large basins usually have a greater time of concentration which allows longer lead time,

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but there are many hydraulic works, operations and cities which require better coverage of monitoring and modelling, taking into account the physical and operational constraints of space, soil occupation and water use, among others.

A flow forecast is an asset for water-resource risk management, reducing damage, providing relief, improving efficient water use and protecting the environment. The integration of monitoring, modelling and operational management is important in constructing an alert system.

Quantitative precipitation forecast (QPF)

The rainfall used in combination with the hydrological model in flow forecasting is the recorded rainfall until time step t . This rainfall is recorded by raingauges and for the time interval between t and t+τ (lead time) the rainfall has to be forecast. In terms of the forecast lead time, nowcasting is for 0-3 hours; short-term is for 6-24 hours; and long-term for 3-24 months lead time (Collier and Krysztofowicz, 2000).

Quantitative precipitation forecasting has been developed, using statistical tools, radar measurements, satellite images and weather modelling. For many years, the rainfall forecast was not taken into account in hydrological flow forecasting. For a basin with a long concentration time, this does not introduce much error for a small lead time, but for flash floods and longer lead times, an estimation of the rainfall is an important requirement. Stochastic models were used to forecast the rainfall in conjunction with hydrological models (Bertoni *et al*, 1992; Mine, 1998) but it did not bring much improvement to the forecast since the rainfall usually does not show significant time-series correlation usually, the radar and telemetric rainfall allow the evaluation of the meteorological conditions and the storm's space distribution and direction. The use of mesoscale weather models to forecast rainfall in a grid comparable to a distributed hydrological model is one of the combined tools which can improve the estimates (Ibbitt *et al.,* 2000). Regional weather models use as a boundary condition the forecast of a global model which simulates the entire Earth. The grid of the regional weather model is smaller than the global with the aim to represent better the changes in the space.

Hydrological models

The hydrological models used in the forecast are empirical, conceptual or a combination of both. Empirical models use mathematical equations without relation to the system's physics. Conceptual models use the hydrological concepts in order to simulate the basin's behaviour. Conceptual models usually have two main components: (*a*) a rainfall-runoff module, which transforms rainfall in runoff through the water balance in the hydrological components such as interception, upper soil zone, ground-water and overland flow; and (*b*) a routeing module, which simulates the flow in the rivers and reservoirs.

Rainfall-runoff models can be lumped or distributed. Lumped models do not usually take into account the spatial variability of rainfall, state variables and model parameters. For small basins, this type of model is very useful, since it has a simple structure and can be easily updated in its parameters or state variables. The distributed models can be distributed by sub-basin or grids. The advantage of distributed models is that they can take into account the spatial variation of physical characteristics of the basin and rainfall conditions. Updating the state variable or the parameters of the distributed models is more complex than a stochastic model, but it can introduce information from the future behaviour of the system. The stochastic model uses past information in order to forecast the future.

The flood-forecasting simulation has the following stages: fitting

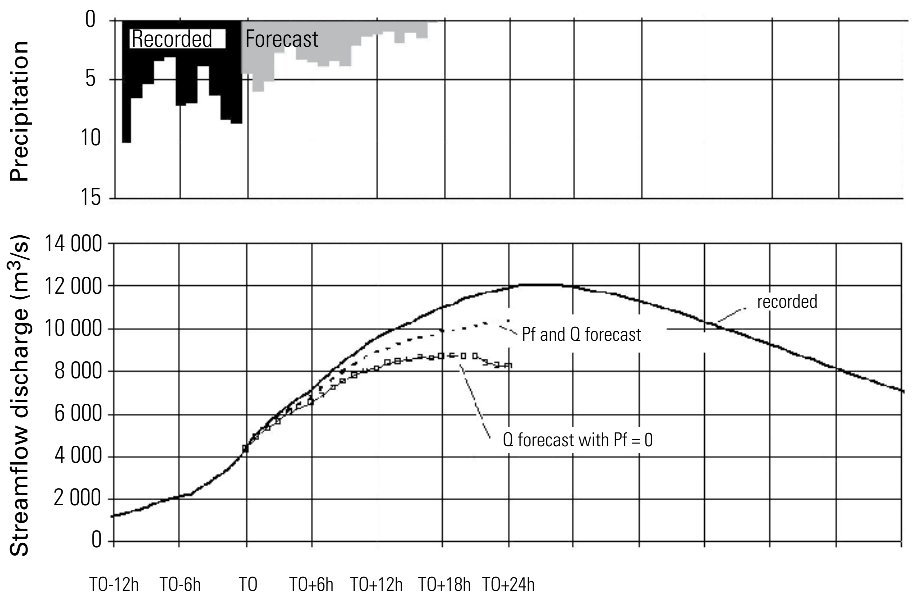

Figure 1 — Rainfall prediction and flow forecast: Q = flow; Pf = rainfall forecast

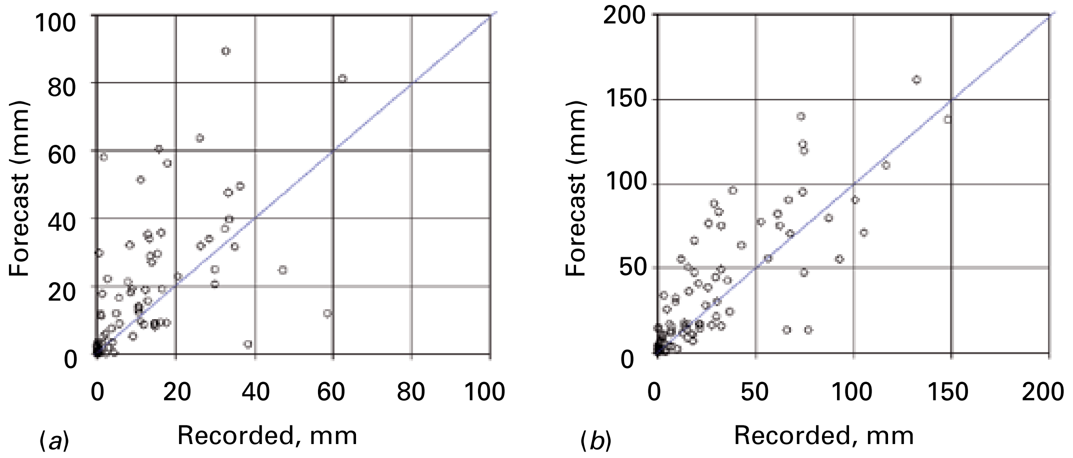

Figure 2 — Accumulated recorded and forecast rainfall with (a) *three and* (b) *seven days lead time by ETA model in Três Marias, San Francisco River basin, Brazil*

and verification of the model parameters and forecasting. In the former two situations, the model shows its behaviour on historical data. During forecasting, it is used with the parameters fitted with forecast rainfall.

Flow forecasting

Flow forecasting can be developed by (*a*) a combination of upstream observations of water level and rainfall recorded (until the time of forecasting) in the intermediate basin; (*b*) rainfall monitored (recorded until the time of the forecast) and a rainfall-runoff model; (*a*) and (*b*) are the procedures used during the last 50 years, based on simple conceptual or stochastic modelling of hydrological variables); or (*c*) rainfall prediction by a weather model, together with rain-fall-runoff modelling for forecast flow (Anderson *et al*., 2002; Koussis *et al*., 2003; and Collischonn *et al*., 2005). The rainfall until the time of the forecast (black rainfall in Figure 1) can be estimated by telemetric raingauges, satellite or radar. In developed countries, the rainfall is estimated by the combination of these tools but, in developing countries, telemetric and radar data are rare. Rainfall estimates by satellite are cheaper but need an evaluation of their feasibility in terms of results.

A quantitative precipitation forecast (QPF) (future time: t+τ, grey in Figure 1) is estimated by the following procedure: (*a*) assuming that the rainfall is nil, which will transfer an important error for flow forecast after a lead time shorter than the time of concentration (lower prediction in Figure 1); (*b*) rainfall predicted by a stochastic model which uses the past information with unreliable outputs; or (*c*) rainfall predicted by a weather model which shows some improvement (upper prediction in Figure 1).

Below are presented some results of the output of the combination of a weather model forecast with a distributed rainfall-runoff model in forecasting the flow in large basins in Brazil.

San Francisco River flow forecasting

The San Francisco River Basin in its section at the Três Marias reservoir has a basin of 50 784 km². The reservoir is used for hydropower. The reservoir inflow forecasting has been developed for dam operation and dam safety. The study (Tucci *et al*, 2005) was developed for the entire San Francisco basin (639 000 km² and 2 700 km) and the results presented were for its upstream basin.

The rainfall was forecast by the regional weather ETA model (Black, 1994), with a grid of 40 x 40 km and a lead time of 10 days. Figure 2

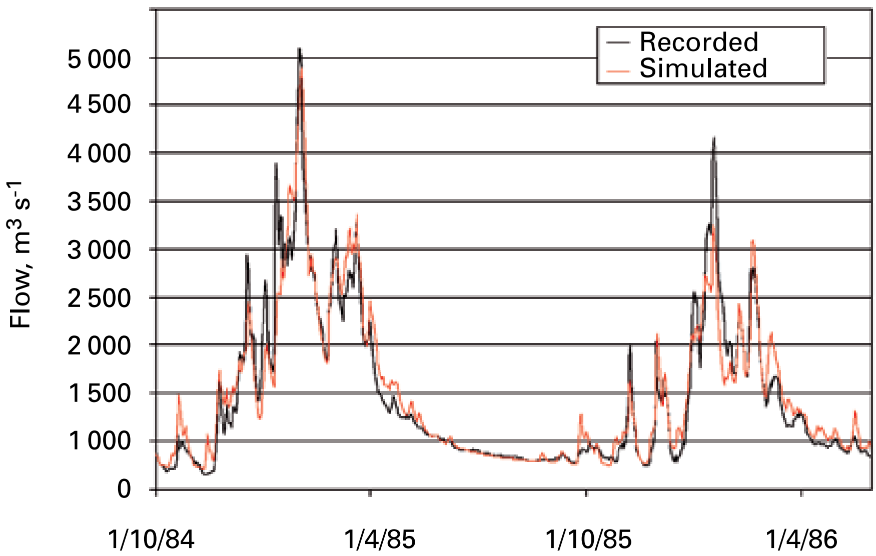

Figure 3 — Recorded and simulated flow by the hydrological model in the San Francisco River at Três Marias from October 1984 to May 1986

shows the recorded and forecast accumulated rainfall with three and seven days lead time. A network of rainfall and flow gauges in the basin supports the forecast.

The distributed hydrological model MGB-IPH (Collischonn and Tucci, 2001) was fitted to the basin (Figure 3). The model was verified with data period and resulted in reliable results. In forecasting, some of its variables can be updated by the recent recorded flow, thus improving the model's performance.

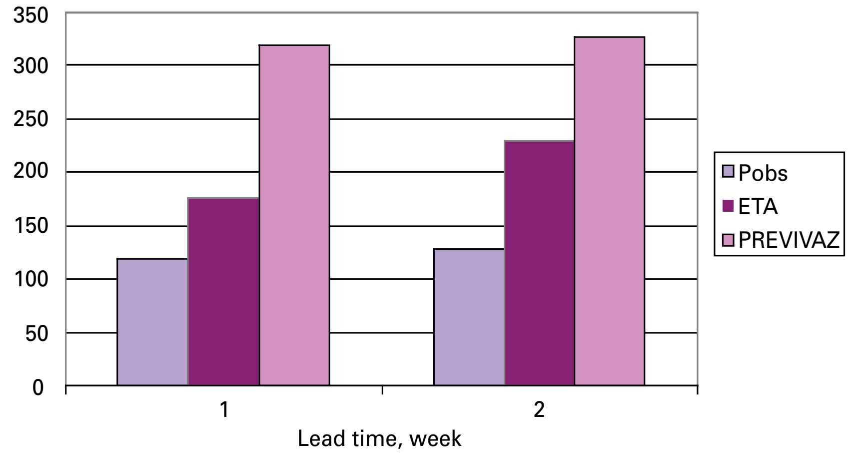

Figure 4 — Mean standard error of the forecast with one and two weeks in advance using (a) *recorded rainfall (Pobs) + hydrological model;* (b) *weather model + hydrological model (ETA);* (c) *stochastic model (PREVIVAZ)*

The following three alternatives were used in forecasting: (*a*) recorded rainfall as input to the hydrological model for flow forecast (Pobs). In this scenario, the error comes from the rainfall-runoff model but it is not real, since the future rainfall is unknown, but measures the limit of the rainfall forecasting; (*b*) rainfall forecast by the ETA weather model as input for the hydrological model; (*c*) stochastic model used by the power company (Previvaz). The stochastic model forecast the future from the past data. It can be seen in Figure 4 that there is an important reduction on the mean standard error of the flow forecast with the integration of the models as compared to 45 per cent reduction error for one week lead time and 27 per cent for the second week of the existing modelling tool. The figure also shows that, in the second week, the forecast using both models has more room for improvement in the rainfall forecast.

Uruguay river basin

Streamflow forecasts based on quantitative precipitation forecasts were also tested in the Uruguay River at Machadinho dam, where the drainage area is almost 32 000 km^2. In this case, reported by Collischonn *et al*. (2005), the model time step was changed to one hour, due to the short response time of the basin and the availability of hourly rainfall data. Rainfall forecasts were obtained from the ARPS model (Xue *et al*., 2003) run in three nested domains, with spatial resolutions of 40, 12 and 4 km. This model has been running operationally since early 2003 at the Federal University of the State of Santa Catarina (Haas, 2002).

Performance of discharge forecasts was evaluated over a continuous 167-day period and from one selected flood event, using rainfall forecasts at three spatial resolutions. These forecasts were also compared with that observed by assuming (*a*) that no further rain would fall, and (*b*) that rainfall forecasts were equal to the rainfall actually recorded. This represents a surrogate for "perfect" rainfall forecasts.

The proposed forecasting methodology was first tested for the 2001 flood event, whose return period was estimated to be near to 100 years. The water level in the reservoir was recorded only once a day at the time of this flood, so the observed hydrograph, derived by reservoir water budget, has a very low time resolution. Figure 5(*a*) shows forecasts issued at 07:00 on 30 September, using rainfall forecasts initiated at 21:00 on 29 September, and using observed rainfall data up to 07:00. At that time, the basin had still not received much rain and the streamflow forecast based on the zero rain forecast shows a recession.

Streamflow forecasts based on numerical weather prediction show better performances, although all three versions of the ARPS model seem to underestimate rainfall for this event. Flow forecasts based on rainfall forecasts at the 40 km resolution of the ARPS model (ARPS-40) correctly predict rising flows, but peak discharge is estimated at less than 3000 m^3/s—far less than the observed peak discharge of close to 14000 m^3/s. The ARPS-12 model performed a little better, giving forecasts of peak discharge near 5 000 m^3/s more than 24 hours in advance. Although the forecast discharge is still underestimated, it would, under operational conditions signal the occurrence of a

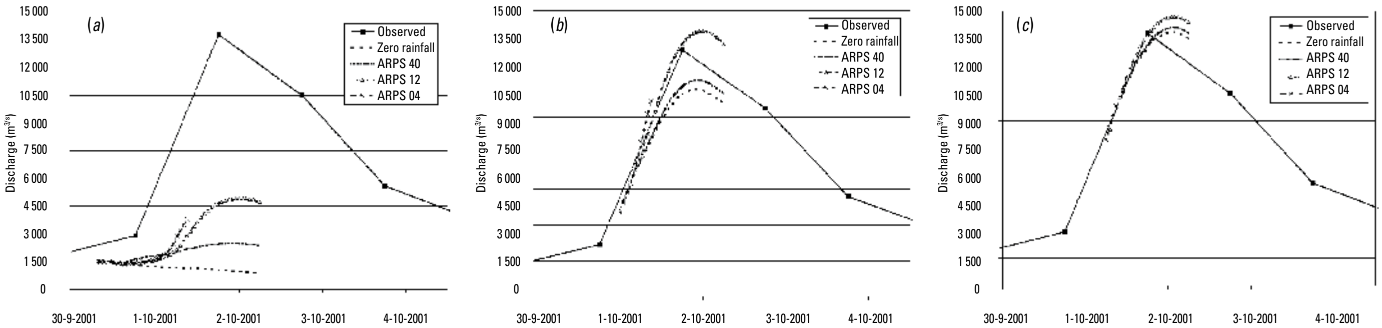

Figure 5 — Incoming flows to the Machadinho reservoir: (a) *forecasts beginning at t0 = 07:00 hours on 30 September 2001;* (b) *forecasts beginning at t0 = 00:00 hours on 1 October 2001; forecasts beginning at t0 = 06:00 hours on 1 October 2001 (after Collischonn* et al., *2005).*

relatively high flood during the coming hours, alerting to the possible need for damage-prevention measures.

As shown in Figure 5(*a*), discharge forecasts based on the 4-km resolution ARPS 4 model seem to be better than the others. ARPS-4 forecasts were only possible for a lead-time of 24 hours, however, which is too short for forecasts up to the hydrograph peak. Figure 5(*b*) shows discharge forecasts performed at midnight on 30 September, with the same rainfall forecast runs of Figure 5(*a*) and observed rainfall data up to midnight. At this time, a great deal of rain had fallen, and flow entering Machadinho showed that peak discharge would rise well above 5 000 m^3/s, as forecast at 07:00. Even the forecast of incoming flow, assuming no further rainfall, showed that the hydrograph would rise for the next 20 hours, with a peak of about 12 000 m^3/s. This forecast, interpreted as the lower limit of an uncertainty range, would be very useful for dam operation purposes. Figure 5(*b*) also shows that forecasts based on all three ARPS models with different resolutions gave estimates of peak discharges well in excess of 12 000 m^3/s, even approaching 15 000 m^3/s in the case of the ARPS-12 model.

Finally, forecasts initiated at 06:00 on 1 October are very similar for the different rainfall forecasts (Figure 5(*c*)). As can be seen, even the zero rainfall forecasts gave good forecasts of incoming flow to the reservoir. Although the timing of the observed peak flow is largely uncertain, it was estimated that peak incoming flows would occur in the early hours of 1 September, so that the good results in Figure 5(*c*) could have been obtained 10 hours in advance of the observed peak flows.

The results obtained for the 167-day continuous period were not so good (Collischonn *et al*., 2005). In many cases, results could have been obtained had it been assumed that no rainfall would occur at all, suggesting that it would be better to ignore future rainfall than to use QPFs.

Conclusion

Flood forecasting has became an important social and economic asset in water-resource management for risk management. The improvement of flow forecast requires research in weather and hydrological modelling. In large basins, it represents an integration of meteorological and hydrological modelling knowledge in space and time with integrated physical behaviour, together with time-series analysis. The results on large basins presented in this paper show that there is much to be developed but there is an improvement as compared to the stochastic tool often used operationally. The use of these tools in developing countries requires an improvement in the network of telemetric monitoring stations. Satellite rainfall estimation has an important future in this type of environment in order to complement the lack of funds and stations.

Some further research recommendations are on updating procedures, using stage and streamflow data to improve initial conditions for the model forecasts; assessing economic and social benefits of improved forecasts (Collischonn *et al*., 2006); adapting reservoir operation rules to the use of streamflow forecasts that may have various degrees of uncertainty (Bravo, 2006); and using data that are available on the global scale, such as satellite estimates of rainfall (Collischonn, 2006).

References

Anderson, M.L.; Z.-Q. Chen; M.L. Kavvas; A. Feldman, 2002: Coupling HEC-HMS with atmospheric models for prediction of watershed Runoff. *Journal of Hydrologic Engineering*, 7, 4, 312-318.

Bertoni, J.C.; C.E.M. Tucci; R.T. Clarke, 1992: Rainfall-based real-time flood forecasting. *Journal of Hydrology*, 131, 313-339

Bravo, J.M., 2006: Reservoir operation optimization based on streamflow forecasts (in Portuguese). M.Sc. dissertation, IPH UFRGS, Brazil.

Black, T.L. , 1994: The new NMC mesoscale ETA model: description and forecast examples. *Weather Analyses and Forecasting*, 9, 265-278.

Collier, C.G., R. Krzysztofowicz, 2000: Quantitative precipitation forecasting, *Journal of Hydrology,* 239,1-2.

Collischonn, B., 2006: Use of TRMM satellite rainfall in a distributed hydrological model (in Portuguese). M.Sc. dissertation IPH UFRGS, Brazil.

Collischonn, W.; J.M. Bravo; C.E.M. Tucci; B.C. Silva, 2006: Assessment of benefits of meteorological forecasts used for operation of multiple-use water reservoirs (in Portuguese). IPH UFRGS.

Collischonn, W; R. Haas; I. Andreolli; C.E.M. Tucci, 2005: Forecasting River Uruguay flow using rainfall forecasts from a regional weather-prediction model. *Journal of Hydrology*, 205, 87-98. .

Collischonn, W.; C.E.M. Tucci, 2001: Hydrologic simulation of large basins (in Portuguese) *Revista Brasileira de Recursos Hídricos*, 6, 1.

Georgakakos, P.K., M.D. Hudlow, 1984: Quantitative Precipitation Forecast Techniques for use in Hydrological Forecasting. *Bull. Am. Meteorol. Soc.*, 65, 1186-1200.

Georgakakos, K.P., R. Krzysztofowicz, 2001:Probabilistic and ensemble forecasting. *Journal of Hydrology,* 249, 1.

Haas, R., 2002 Simulation of orographic precipitation associated to an extra tropical cyclone (in Portuguese). Ph.D. thesis, IAG USP, Brazil.

Ibitt, R.P., R.D. Henderson; J. Copeland; D.S. Wratt, 2000: Simulating mountain runoff with mesoscale weather model rainfall estimates: a New Zealand experience. *Journal of Hydrology,* 239, 19-32

Koussis, A.D., K. Lagouvardos; K. Mazi, V. Kotroni, D. Sitzmann, J. Lang, H. Zaiss, A. Buzzi, P. Malguzzi, 2003: Flood forecasts for urban basins with integrated hydro-meteorological model. J*ournal of Hydrologic Engineering*, 8, 1, 1-11.

Krzystofowicz, R., 1995: Recent advances associated with flood forecast and warning systems. *Ver. Geophys.*, 33 Suppl.

Mine, M., 1998: *Método determinístico para minimizar o conflito entre gerar energia e controlar cheias*. Tese de doutorado, Instituto de Pesquisas Hidráulicas. UFRGS.

Tucci, C.E.M., W. Collishonn, B.C. da Silva, P. da Silva Dias, G. Sampaio, Sin Chan Chou, J. Marengo, R.T. Clarke, 2005: Previsão Hidroclimática no rio São Francisco. ANEEL IPH-UFRGS, 400 pp.

Xue, M., D. H. Wang, J.D. Gao, K. Brewster, K.K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, 82, 139-170.